3.0 Sensitivity Analysis

This section of ASP II addresses sensitivity analyses conducted for 12 functional elements (FEs) as defined in the “RF Sensor Functional Area Template (FAT)” shown in figure 1.3-1 of section 1. The goals of the sensitivity analyses performed for ALARM are to identify critical input parameters for each FE and determine the measurement accuracy required for critical parameters in order to produce credible model results. Other objectives of the sensitivity analyses are to uncover errors in the implementation of model FEs by assessing the reasonableness of FE outputs and define assumptions and limitations in the application of individual FEs.

A summary of the results of sensitivity analyses is given below. Following the summary, a description of the methodology used in the conduct of sensitivity analysis is provided. Details of sensitivity analysis procedures can be found in the *SMART Process Document* [A.2-1].

3.0.1 Summary of Results

Table 3.0-1 summarizes the sensitivity of ALARM to the input parameters varied for the 12 FEs addressed in this document. The sensitivity is rated either “sensitive” or “insensitive.” The criterion for “sensitive” is that variations in the input parameter cause a 5% or greater change in normalized mean target detection range. Conversely, ALARM is considered “insensitive” if the impact on normalized mean target detection range is less than 5%. (See section 3.0.3 for an explanation of the criteria chosen for the sensitivity analyses and a definition of normalized mean target detection range.)

Table 3.0-1 Summary of Sensitivity Analyses Conducted to Date for ALARM

Functional Element	Parameter	Sensitivity
Static RCS	Static RCS Resolution	Sensitive
Dynamic RCS	Rotor RCS Resolution	Sensitive
Fluctuations	Target Statistical Type	Sensitive
On-Board Noise	Jammer Antenna Gain Pattern	Sensitive
	Burn-Through Detection Threshold	Sensitive
Stand-Off Noise	Noise Jamming Burn-Through Threshold	Sensitive
Clutter	MTI Clutter Rejection	Sensitive
	Maximum Off-Boresight Angle for Clutter Calculations	Insensitive
	Incremental Off-Boresight Angle for Clutter Calculations	Insensitive
Multipath / Diffraction	Surface Conductivity	Insensitive
	Refractivity Factor	Sensitive
	Target Altitude & Radar Frequency	Sensitive

Table 3.0-1 Summary of Sensitivity Analyses Conducted to Date for ALARM

Functional Element	Parameter	Sensitivity
Atmospheric Attenuation	Atmospheric Conditions and Radar Frequency	Sensitive
	Atmospheric Conditions and Radar Type	Sensitive
Waveform Generator	Transmitter Power	Insensitive
	Radar Pulse Width and Noise Bandwidth	Insensitive
	Frequency	Sensitive
Antenna Gain	Gain Resolution	Insensitive
	2-D vs 3-D Patterns	Sensitive
Antenna Scan	Antenna Scan Rate and Target Velocity	Sensitive
MTI Clutter Rejection	Target Signal Pulse Amplitude	Sensitive

3.0.2 Implications for Model Use

As a result of the sensitivity analyses, certain model limitations and constraints for model application have been identified and are discussed below for each functional element.

Static RCS: The ALARM estimate of target detection range is sensitive to the angular resolution of target RCS. However, validation of the Static RCS functional element requires only parameter validation since RCS is a model input. Because RCS resolution has a significant impact on the prediction of target detection, it should be measured at an angular resolution of at least 0.1° in both azimuth and elevation planes. It is important to note that the measured radar cross section of the target is a required parameter for model-level validation of other functional elements and will retain the same measurement resolution requirement.

The ALARM model user should be aware that the use of cell-averaged data over large resolution cell limits may lead to significant errors in determining target detection range. This may be particularly applicable to low-observable targets which will typically have low average cross section but will likely contain a few high RCS specular points. These specular points will not be observable if using RCS which has been averaged over large angular cell limits.

Dynamic RCS: ALARM uses dynamic RCS data as an input to the model so it is not essential to collect dynamic RCS data to validate this specific function. However, for validation of other functions and for overall model validation, measured dynamic RCS data will be required. The doppler frequency resolution requirements for collection of rotor blade measurement cannot be explicitly defined since the rotor blade RCS of each vehicle type will be unique. Nevertheless, it is important that the frequency resolution, when measuring the dynamic RCS, be adequate to assure that all major specular reflectors of the rotor blade are included within the measured data. This indicates that the dynamic RCS of the rotor blade should be measured at the highest resolution that is practical. In application of the measured data as model input, the resolution can be user defined by reviewing the data and selecting a frequency resolution that assures that all major specular reflectors are included.

Fluctuations: Target signal fluctuation statistics are not defined for most target types. Since target fluctuation characteristics can significantly impact the prediction of target detection, collection of validation data for this functional element is of the highest priority. Assuming that target fluctuations are unique for each target and flight conditions, validation data collection should be conducted for a broad array of target types, target flight conditions, and radar types. It is essential to measure pulse-to-pulse signal amplitude, system integration gain, and the threshold for detection for each target type and flight condition in order to validate this functional element.

The user should be aware of the sensitivity of the model to the choice of statistical target and should be further aware that the specific target of interest may not fall within the statistical target types currently available in ALARM.

On-Board Noise: The sensitivity of the burn-through detection threshold on target detectability in the presence of on-board jamming is significant. To validate this functional element, it is apparent that the signal-to-jamming threshold at target burn-through should be measured to an accuracy of less than 1.0 dB. This is a significant finding in that the variability between operators, radar display settings, and jammer noise modulation parameters may result in a burn-through threshold variability of greater than the 1.0 dB measurement requirement.

The sensitivity analyses also indicate that the effectiveness of on-board jamming is significantly impacted by the directionality of the jammer antenna. The model user should be aware that the omission of a fixed-position directional antenna in ALARM may lead to significant errors in predicting jammer effectiveness.

Stand-Off Noise: The sensitivity of target detectability to the burn-through detection threshold in the presence of stand-off jamming is significant. To validate this functional element, it is apparent that the signal-to-jamming threshold at target burn-through should be measured to an accuracy of less than 1.0 dB. This is a significant finding in that the variability between operators, radar display settings, and jammer noise modulation parameters may result in a burn-through threshold variability of greater than the 1.0 dB measurement requirement. The user of the model should be aware of this potential variability in the burn-through detection threshold and its impact on predicted target burn-through range.

Clutter: For MTI radars, face validation of the clutter function appears adequate since clutter is suppressed below the system noise level and does not impact target detection. However, for pulsed radars without MTI it will be necessary to validate the clutter function. The key parameters to be measured are clutter signal return, antenna gain through the first sidelobes, and radar pulse width.

Multipath/Diffraction: Multipath propagation directly impacts target detection; sensitivity analysis indicates that ALARM is sensitive to the refractivity factor and target altitude. For credible model results, the user should determine the refractivity factor for the specific scenario and climatic conditions of interest, rather than using the more universally accepted value of 4/3 earth's radius. At very low-altitude, nap-of-the-earth flight profiles, ALARM is sensitive to target altitude. The user should not expect to replicate multipath propagation effects unless the target altitude is known to an accuracy of less than 1.0 meter. At higher altitudes, the impact of target altitude on multipath propagation appears to be less important. This apparent insensitivity is actually due to a relative decrease in antenna gain in the direction of the multipath specular point, rather than changes in target altitude. If the radar of interest has a broad antenna beam in the elevation plane, typical of some early warning (EW) and search radars, the gain of the antenna at the multipath specular point may remain high and multipath propagation will impact targets at higher altitudes.

Atmospheric Attenuation: The sensitivity of the functional element is significant for radars operating within the high microwave frequency region. Although validation of the functional element is a low priority and the algorithms used for calculation of atmospheric attenuation are empirically based, there is a need to collect validation data to confirm the generality of the categorized atmospheric conditions. That is, it is necessary to investigate the frequency of occurrence of the standard categories of atmospheric conditions as functions of geography, season of the year, and probable daily changes in conditions.

The user of the model should be aware that for some radar/target/atmospheric conditions the Standard Day atmosphere, as modeled in ALARM, could result in significant error in the prediction of target detection. Even if ALARM were modified to represent other atmospheric conditions, it is not possible to accurately predict these conditions for a specific use of the model. Applying the Standard Day conditions with an awareness of the maximum errors in target detection, induced by the extremes in atmospheric conditions, is likely the best compromise.

Waveform Generator: Initial target detection range is impacted slightly by varying transmitter power. To assure accurate model target detection range predictions, the candidate radar peak pulse power should be measured to an accuracy of ±10% of the nominal value for the radar type under test.

Initial target detection range is slightly impacted by changes in pulse width and receiver bandwidth. The radar pulse width and receiver bandwidth should be measured to an accuracy of ±10% of the nominal values for the radar type under test.

Initial target detection range is impacted significantly by changes in transmission frequency. Radar transmitter frequency measurement accuracy of less than 10% of the nominal value for the radar type under test is required for validation data measurement.

Antenna Gain: Sensitivity analysis results indicate that ALARM is insensitive to changes in antenna resolution for the perfect pointing assumption. However, it should be noted that without perfect pointing, in a high-clutter or SOJ environment, antenna resolution could be a more significant factor.

The sensitivity analysis was limited to a single antenna type having a $((\sin x) / x)^2$ gain response and a beamwidth of 1.0˚. However, the analysis indicates significant differences in off-boresight gains. It is apparent that actual 3-D antenna gain patterns should be used when available, particularly in high-clutter and side-lobe jamming environments.

Antenna Scan: Depending on the radar’s scan rate, the impact on target detection can be large. It must be noted that the detection range computed by ALARM is not incorrect, but is the “best possible”; that is, detection of the target occurs at the very first opportunity. The ALARM assumption of perfect antenna pointing yields the most meaningful measure of radar detection performance, the maximum possible target detection range.

MTI Clutter Rejection: Although the algorithms used in the model to represent the MTI function may be valid for a steady target signal, sensitivity analysis indicates that there may be significant error in the modeled MTI response for fluctuating target signals. In collecting measured MTI response validation data, it will be essential to measure the MTI response for both fluctuating and steady target signals. If the measured response to fluctuating targets is significant, relative to the measured MTI response to a steady target, it may be advisable to characterize target fluctuations and modify the MTI model algorithms to more validly represent the MTI function.

3.0.3 Method of Analysis

Criteria: Sensitivity analysis is designed to first determine the impact of changes in functional element input parameters on a specific functional element measure of performance (MOP), and then to assess the impact of the changes in FE input parameters on a common overall model measure of performance.

Although each function-level measure of performance is dependent upon the specific functional element, the general criteria of significance selected for the ALARM FE-level sensitivity analysis is a 3.0 dB change in function-level output for the input parameter variation. For example, a 3.0 dB difference in atmospheric attenuation for a change in atmospheric conditions from "Standard

Day" atmosphere to "Arctic Winter" atmosphere would be considered significant at the function level and would indicate a probable impact on overall model performance.

At the model level, there is a measure of performance common to all functional elements, the maximum target detection range. A change of greater than 5% of normalized mean target detection range as a function of FE level input parameter variation is considered significant and will impact validation data collection requirements, model constraints, and model limitations. The choice of 5% is derived from its use in experimental statistics, where it is regarded as a standard level of significance [A.2-21].

Analytic Procedures: A series of model runs is made for each FE subjected to sensitivity analysis. For the model-level analysis, ALARM is executed in Contour Plot mode. In this mode, the target is “flown” from north to south on several parallel flight paths. The first flight path is a user-specified maximum distance “west” of the radar site; subsequent flight paths approach the radar site from the “west” and are offset from the initial path in equal increments. The final flight path is at the specified maximum distance “east” of the site. The distance from the radar to an offset flight path is called the offset range; the distance from the radar to the target is called the slant range. For most of the FE-level sensitivity analyses, ALARM is executed in Flight Path mode, where a single flight path is input to the model.

For the Contour Plot mode runs, the slant range at the time initial target detection occurs in each offset flight path is recorded. Detection ranges for the baseline model run are then compared with those of the test caes. For the Flight Path mode runs, the FE-level output at each flight path waypoint is recorded. The baseline model run results are then compared with those of the test cases.

The baseline ALARM input decks used for these sensitivity analyses are given in Appendix B. The baseline radar is a pulsed MTI radar with two delay lines, transmitting at a frequency of 14875 MHz. For the Contour Plot mode runs, the plot range is 70 km, the target’s altitude is 500 ft, and the target speed is 775.52 ft/sec. Multipath and clutter are turned off.

Two primary methods are used to analyze the results of the model runs made for each FE: (1) generation of X-Y plots to aid in visually evaluating both model-level and FE-level results and (2) statistical analysis of normalized mean differences in target detection ranges (model-level results).

X-Y Plots: When executed in Contour Plot mode, the ALARM output is a contour plot; figure 3.0-1 is a typical contour plot. This type of plot gives the analyst a good perspective of radar performance against a given target. However, it does not provide the best picture of initial target detection range. For that perspective, the point where initial detection of the target occurs in each flight path is plotted, giving a curve that describes initial detection for each flight path. Figure 3.0-2 is an example of the detection range plots used in the sensitivity analyses of ALARM.

A second type of plot, for the cases where ALARM is executed in Flight Path mode, is also used in the analysis. A typical example of this type of plot is displayed in figure 3.0-3, which shows the changes in the value of an FE output at each flight path point, for three different values of an FE input. This type of plot visually demonstrates the impact of changes in the FE input on the FE output, along a single flight path.

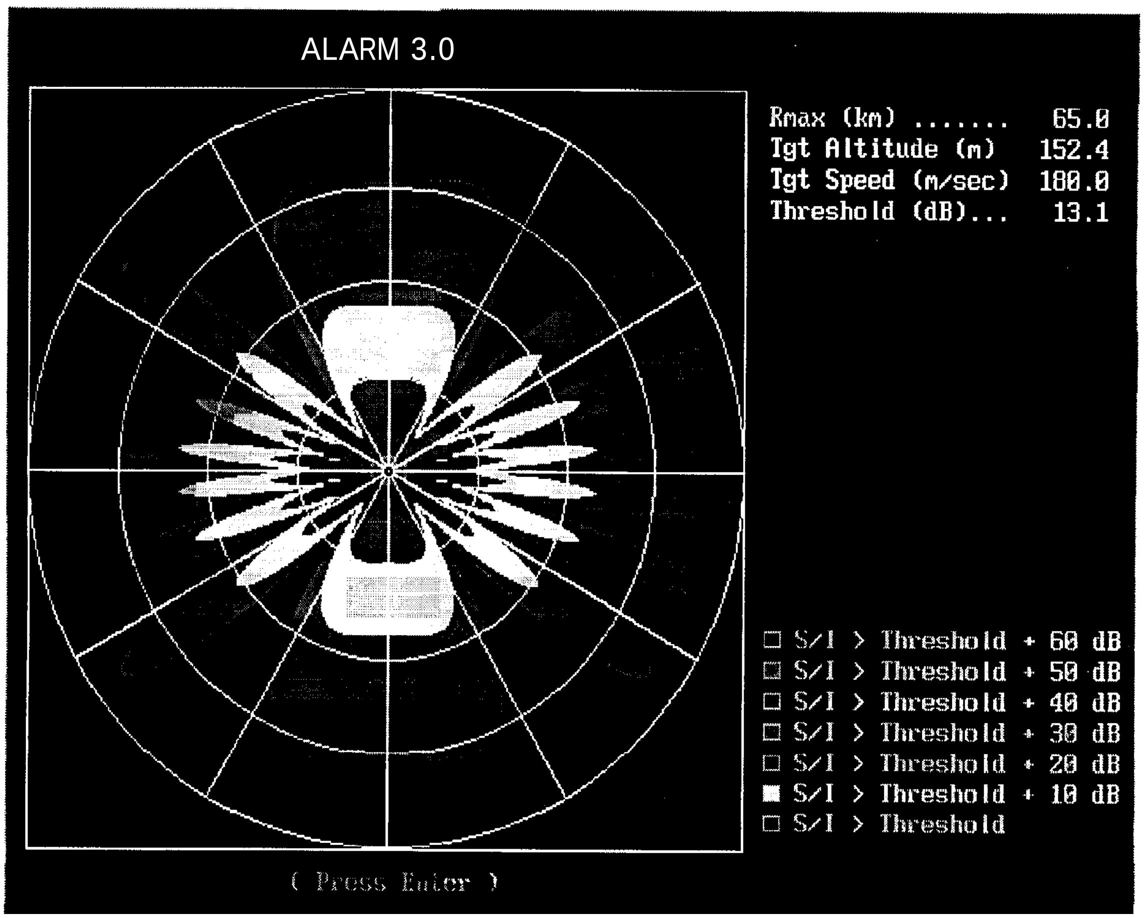

Figure 3.0-1 ALARM Contour Plot

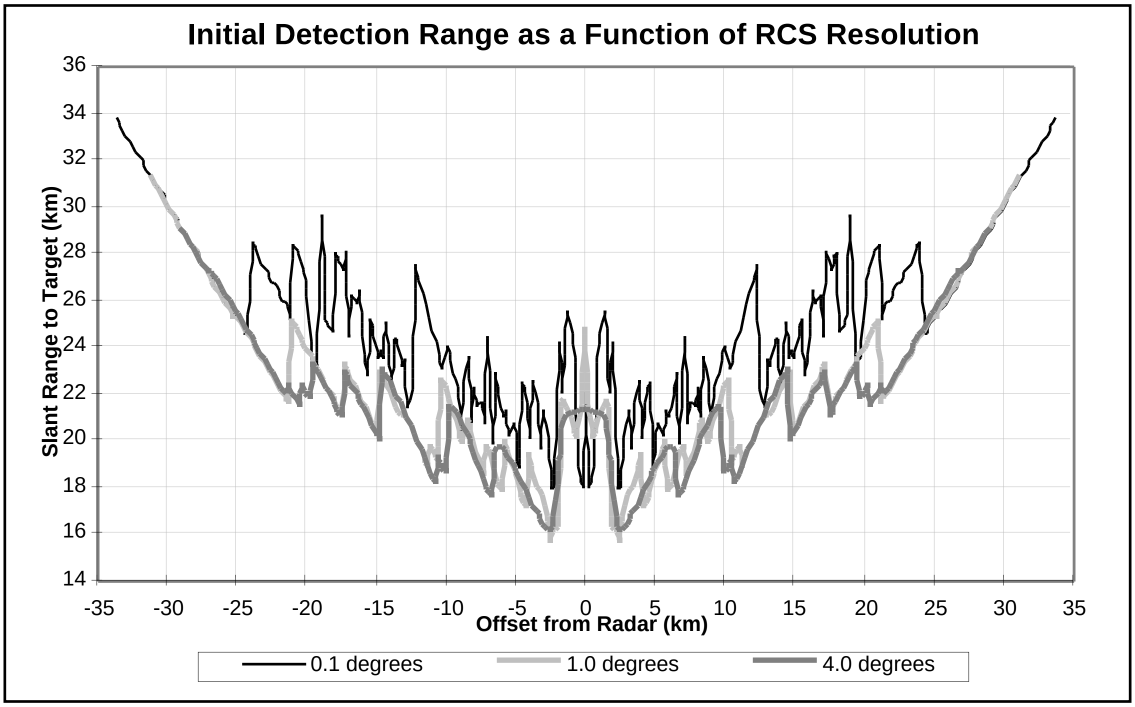

Figure 3.0-2 ALARM Initial Target Detection Range Plot

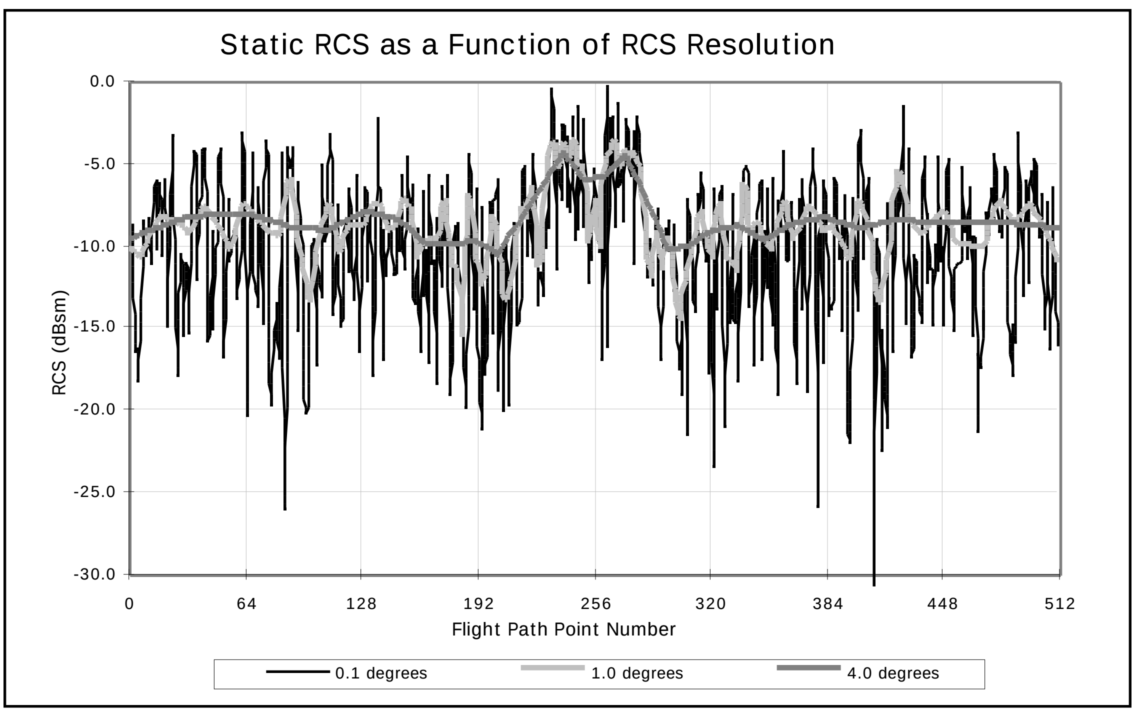

Figure 3.0-3 ALARM FE Output Plot

Statistical Analysis: The statistic of interest calculated during sensitivity analysis is the normalized mean target detection range difference. This value characterizes differences in target detection range in relative, rather than absolute, terms. For example, consider the data displayed in table 3.0-2, representing three data points for two different (hypothetical) model runs:

Table 3.0-2 Example Functional Element Data Set

Data Set	Input-Varied Detection Range (km)	Baseline Detection Range (km)	Absolute Difference (km)	Relative Difference (%)
1	2	20	18	10
	3	30	27	10
	4	40	36	10
2	200	2000	1800	10
	300	3000	2700	10
	400	4000	3600	10

In absolute terms, the differences in detection range for the second set of data points appear to be much larger than the differences in the first set. However, the relative differences are the same for both cases, 10%.

The method used to derive the normalized mean difference consists of the following steps:

1. Calculate the mean detection range for each model run comprising the analyses. Designate one model run as the baseline case.

2. Calculate the normalized mean difference in target detection range between the baseline case and each of the other model runs using equation (3.0-1):

$$R_N = \frac{\bar{R}_1 - \bar{R}_2}{\bar{R}_1 + \bar{R}_2} \tag{3.0-1}$$

where: $\bar{R}_1$ = mean target detection range using the input-varied parameter
$\bar{R}_2$ = mean target detection range using the baseline case

The normalized mean difference is a value in the interval [–1.0, +1.0]; a normalized difference of 0.0 indicates that the input-varied model run replicates the baseline functional element performance.

The absolute difference in detection range between input-varied and baseline functional element performance can be determined as shown in equation (3.0-2), which is based on equation (3.0-1). For example, if the average detection range of the baseline radar is 40.0 km and the normalized mean detection range difference is 0.01, then the mean detection range of the input-varied radar is:

$$\begin{aligned} 0.01 &= \frac{\bar{R}_1 - 40\text{ km}}{\bar{R}_1 + 40\text{ km}} \\ \bar{R}_1 &= 40.8\text{ km} \end{aligned} \qquad (3.0\text{-}2)$$

The normalized mean difference can also be expressed as a percentage. For example, if two sets of data vary on average by 10%, then the normalized mean difference would be 0.05 if the test case mean was larger than the baseline mean. The factor can be positive or negative depending on which way the test case varies from the baseline case. The percentage is computed using equation (3.0-3):

$$\begin{aligned} \text{Change} &= \frac{1 + R_N}{1 - R_N} \\ \%\ \text{Change} &= 100 \times (\text{Change} - 1) \end{aligned} \qquad (3.0\text{-}3)$$

Table 3.0-3 shows the normalized mean difference for various percentage differences between comparable data sets. Both the normalized mean difference and the relative percentage change it represents are reported for each FE.

Table 3.0-3 Normalized Detection Range Factors

Relative Change	Normalized Values	
	Positive Changes	Negative Changes
1%	0.004975	–0.005025
5%	0.024390	–0.025641
10%	0.047619	–0.052632
20%	0.090909	–0.111111
50%	0.200000	–0.333333
100%	0.333333	–1.000000

Analysis Results: Results of the statistical analysis are presented in a table describing the test cases, normalized mean differences, percentage of change in normalized mean differences, and test case means and standard deviations. Table 3.0-4 is a typical analysis results table.

Table 3.0-4 Detection Range Statistics as a Function of Changes in RCS Resolution

RCS Resolution	Mean (m)	σ (m)	Normalized Mean Difference	Percent Change
0.1˚ (baseline)	24970	3.61	-	-
1˚	22539	3.59	–0.04815	–9.19
4˚	21691	3.04	–0.05863	–11.08